

Long-Range Underwater Sound Propagation: Environmental Variability, Signal Stability and Signal Coherence

Michael G. Brown

Division of Applied Marine Physics

Rosenstiel School of Marine and Atmospheric Science

University of Miami

4600 Rickenbacker Causeway

Miami, FL 33149-1098

Phone: (305) 421-4640 Fax: (305) 421-4701 Email: mbrown@rsmas.miami.edu

Award #: N000141210182

<http://www.rsmas.miami.edu/people/faculty-index/?p=michael-g.-brown>

LONG-TERM GOAL

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean, and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

Work over the past two years or so has focused on noise interferometry – the process by which an approximation to the transient Green's function $G(x_A|x_B, t)$ between locations x_A and x_B is estimated by cross-correlating records of ambient noise measured at x_A and x_B . In that context, our objective is to investigate and identify the limitations of noise interferometry for remote sensing applications in a variety of ocean environments.

APPROACH

The objective stated above objective has been addressed using a combination of field experiments, theoretical investigations, simulations, and signal processing algorithm development. The stated objective is broad and geographically unconstrained. With this in mind, coupled with realistic fiscal constraints associated with the cost of doing ocean acoustic field work, our approach has been to perform field work in the Straits of Florida, the logistics of which is very simple. That field work has been partially supported by NSF. Field work has been complemented by data-driven theoretical investigations, simulations and signal processing algorithm development.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Long-Range Underwater Sound Propagation: Environmental Variability, Signal Stability and Signal Coherence				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Miami,Rosenstiel School of Marine and Atmospheric Science (RSMAS),4600 Rickenbacker Causeway,Miami,FL,33149				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

WORK COMPLETED

The work listed below is in various stages of completion. The work listed in items 1, 2 and 3 is complete. The work described in item 4 is ongoing.

1. LOAPEX analysis

The PI's work (in collaboration with I Udovydchenkov at WHOI and the experimental groups at APL/UW and SIO) on the analysis of LOAPEX measurements is near completion. This effort is closely linked to earlier theoretical work on modal group time spreads work by Udovydchenkov and Brown (2008). Two papers have been written (Udovydchenkov et al., 2012a and b). The first paper focuses on near-axial modes, corresponding to small mode numbers. Those modes are the simplest to deal with from a measurement perspective, but from the perspective of scattering theory, those modes present special challenges. The second paper focuses on higher order modes. From the perspective of the scattering theory that has been developed, those modes present no special challenges, but, because the LOAPEX experiment was not designed to measure those modes, they present special signal processing difficulties. In both papers, in spite of the particular challenges present, agreement between data-based estimates of modal group time spreads and theoretical predictions is good.

2. Weakly dispersive modal pulses

A modal pulse is a finite-bandwidth distribution of energy with fixed mode number. Weakly dispersive modal pulses (WDMPs) are special cases of modal pulses for which $I(m,f)\beta(m,f) \sim 0$ across the entire frequency band. WDMPs are closely related to weakly divergent beams (studied earlier by Brekhovskikh, Kurtepov, Petukhov and others), which have near-zero spreading loss in the vertical plane. WDMPs have the special property that they may propagate long distances – many hundreds of km – without undergoing distortion. Loosely speaking, this means that a transmitted signal can be recovered at long range without performing any channel equalization. WDMPs are thus well suited to communications and surveillance applications. Two papers on WDMPs have been written. The first (Brown and Udovydchenkov, 2013) describes the relevant theory. The second (Udovydchenkov, Brown, et al., 2013) demonstrates – using data collected during the 2004 LOAPEX experiment – the utility and robustness of WDMPs in deep ocean propagation.

3. Glider communications

With colleagues H Song, R Andrew and B Howe, the feasibility of communications with $f_0 = 75$ Hz, $\Delta f = 30$ Hz between a fixed source and a glider at a range of several hundred km has been demonstrated (Song et al., 2014). In addition to the usual challenges of low SNR and a fluctuating sound channel, Doppler corrections are a critically important element of glider communications.

4. Noise interferometry

Using a combination of ONR and NSF funds three autonomous ambient noise recording systems have been built and deployed three times in the Florida Straits. Some analysis has been performed and two papers describing preliminary results have been written (Brown et al., 2014; Godin et al., 2014).

The first paper (Brown et al., 2014) demonstrates the feasibility of noise interferometry in a strongly multipathing coastal environment at ranges of 5 and 10 km. It was shown that in that environment stable correlation functions can be obtained using coherent stacking intervals as short as 30 hours, in rough agreement with theoretical predictions. Also, this paper quantifies the manner in which the correlation function can be modeled as a weighted Green's function. In that environment two weighting functions are important – a dipole excitation term and a term that accounts for coherence loss due to tidal fluctuations. Introduction of these weighting functions allows wave-equation-based analysis procedures to be pursued. These include the possibility of performing wave-equation-based waveform inversions of measured correlation functions, a topic that we are now pursuing.

The second paper (Godin, et al., 2014) demonstrates the feasibility of measuring depth-averaged currents using noise interferometry. This is made possible using noise interferometry by the fact that computed correlation functions at positive and negative lag correspond to Green's functions with effective source and receiver positions reversed. Because sound travelling in the direction of a background current travels faster than sound travelling in the direction opposing the current, travel time difference can be used to estimate the average current.

RESULTS

Our relatively recent interest in, and work on, noise interferometry is just beginning to bear fruit. We have successfully demonstrated the feasibility of noise interferometry at ranges of 5 and 10 km in water depths of 100 m, 600 m and 800 m. (Previous demonstrations were at much shorter ranges.) We have demonstrated the feasibility of estimating ocean currents using noise interferometry. We have made significant progress on quantifying differences between correlation functions and Green's functions, and we have initiated wave-equation-based modeling of correlation functions. On a longer timescale (the last decade roughly), we have shown that wavefield structure and stability are, to a surprisingly large degree, controlled by a property (the ray-based stability parameter α or the asymptotically equivalent mode-based waveguide invariant β) of the background sound speed profile, rather than details of the sound speed perturbation. This statement is supported by observations, numerical simulations, and theoretical analysis, both ray- and mode-based.

IMPACT/APPLICATION

Our work is contributing to an improved understanding of the basic physics of low-frequency long-range sound propagation in the ocean, and the associated loss of signal stability and coherence imposed by environmental variability. This knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

Our results are being used to interpret (reinterpret, in some cases) data collected in long-range propagation experiments, e.g. AET, SPICEX, LOAPEX and PhilSea. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI's principal collaborators are O. Godin at ESRL/UColorado; I. Udovydchenkov at MITRE (formerly at WHOI), R. Andrew and B. Dushaw at APL/UW; P. Worcester, W. Munk, B. Cornuelle, and M. Dzieciuch at SIO; B. Howe at UHawaii; and J. Colosi at NPS.

REFERENCES

- Udovydchenkov, I. A., and M. G. Brown, 2008, Modal group time spreads in weakly range-dependent deep ocean environments, *J. Acoust. Soc. Am.* **123**, 41-50.
- Udovydchenkov, I. A., M. G. Brown, T. F. Duda, J. A. Mercer, R. K. Andrew, P. F. Worcester, M. A. Dzieciuch, B. M. Howe and J. A. Colosi, 2012a, Modal analysis of the range evolution of broadband wavefields in the North Pacific Ocean: Low mode numbers, *J. Acoust. Soc. Am.* **131**, 4409-4427.
- Udovydchenkov, I. A., M. G. Brown and T. F. Duda, 2012b, Piecewise coherent mode processing acoustic measurements made on two nearby vertical line arrays, *J. Acoust. Soc. Am.* **131**, EL492-EL498.
- Brown, M. G., and I. A. Udovydchenkov, 2013, Underwater communication using weakly dispersive modes, *Acoust. Phys.* **59**, 533-538.
- Udovydchenkov, I. A., M. G. Brown, T. F. Duda, P. F. Worcester, M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, B. M. Howe, J. A. Colosi, 2013, Weakly dispersive modal pulse propagation in the North Pacific Ocean, *J. Acoust. Soc. Am.* **134**, 3386-3394.
- Song, H. C., B. M. Howe, M. G. Brown and R. K. Andrew, 2014, Diversity-based acoustic communication with a glider in deep water, *J. Acoust. Soc. Am.* **135**, 1023-1026, doi:10.1121/1.4864299
- Brown, M. G., O. A. Godin, N. J. Williams, N. A. Zaboltn, L. Zaboltna and G. J. Banker, 2014, Acoustic Green's function extraction from ambient noise in a coastal ocean environment, *Geophys. Res. Lett.* **41**, doi:10.1002/2014GL060926.
- Godin, O. A., M. G. Brown, N. A. Zaboltn, L. Zaboltna and N. J. Williams, 2014, Passive acoustic measurements of flow velocity in the Straits of Florida, submitted to *Geoscience Lett.*

PUBLICATIONS

- Udovydchenkov, I. A., M. G. Brown, T. F. Duda, J. A. Mercer, R. K. Andrew, P. F. Worcester, M. A. Dzieciuch, B. M. Howe and J. A. Colosi, 2012a, Modal analysis of the range evolution of broadband wavefields in the North Pacific Ocean: Low mode numbers, *J. Acoust. Soc. Am.* **131**, 4409-4427. [published, refereed]
- Udovydchenkov, I. A., M. G. Brown and T. F. Duda, 2012b, Piecewise coherent mode processing acoustic measurements made on two nearby vertical line arrays, *J. Acoust. Soc. Am.* **131**, EL492-EL498. [published, refereed]
- Brown, M. G., and I. A. Udovydchenkov, 2013, Underwater communication using weakly dispersive modes, *Acoust. Phys.* **59**, 533-538. [published, refereed]

- Udovydchenkov, I. A., M. G. Brown, T. F. Duda, P. F. Worcester, M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, B. M. Howe, J. A. Colosi, 2013, Weakly dispersive modal pulse propagation in the North Pacific Ocean, *J. Acoust. Soc. Am.* **134**, 3386-3394. [published, refereed]
- Song, H. C., B. M. Howe, M. G. Brown and R. K. Andrew, 2014, Diversity-based acoustic communication with a glider in deep water, *J. Acoust. Soc. Am.* **135**, 1023-1026, doi:10.1121/1.4864299 [published, refereed]
- Brown, M. G., O. A. Godin, N. J. Williams, N. A. Zabotin, L. Zabolina and G. J. Banker, 2014, Acoustic Green's function extraction from ambient noise in a coastal ocean environment, *Geophys. Res. Lett.* **41**, doi:10.1002/2014GL060926. [published, refereed]
- Godin, O. A., M. G. Brown, N. A. Zabotin, L. Zabolina and N. J. Williams, 2014, Passive acoustic measurements of flow velocity in the Straits of Florida, submitted to *Geoscience Lett.* [refereed]